Secondary Mineral Evidence of Large-Scale Water Table Fluctuations at Yucca Mountain, Nye County, Nevada

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At Yucca Mountain, which is currently under consideration as a potential permanent underground repository for high-level radioactive wastes, the present-day water table is 500 to 700 m deep (Luckey et al., 1996). This thick unsaturated zone (UZ) is part of the natural barrier system and is regarded as a positive attribute of the potential site.

The USGS has studied the stable isotopes and petrography of secondary calcite and silica minerals that coat open spaces in the UZ and form irregular veins and masses in the saturated zone (SZ) (Szabo and Kyser, 1990; Whelan et al., 1994). These studies have revealed a thick barren zone in which secondary mineral occurrences are rare. This barren zone extends from about 100 m above to more than 300 m below the present water table (fig. 1). Shallow ground waters beneath Yucca Mountain are undersaturated with respect to calcite (Benson and McKinley, 1985) and have the potential to dissolve calcite along active flowpaths in this interval. The rare occurrences of secondary calcite in this barren interval appear to have formed at times when the water table was much lower than at present.

Strontium isotope studies of secondary calcite within Yucca Mountain (Marshall et al., 1993), and regional analysis of ground water discharge deposits indicate that water table elevations were higher in the past (Quade et al., 1995). Discharge deposits at paleospring sites in southern Crater Flat, 15 to 20 km southwest of Yucca Mountain, indicate at least a 100 m rise in the water table during the late Pleistocene (Paces et al., 1997). Past water table rises beneath Yucca Mountain of ~100 m are likely and a possible explanation for the paucity of secondary minerals within the lower UZ, although Ca depletion in the zeolitic tuffs through cation exchange may produce calcite undersaturation of percolating waters. Only drillhole USW G-2 contains significant amounts of calcite within the lower 100 m of the UZ.

Drusy coatings of free-growing calcite and silica phases formed in the UZ from surface percolation fluxes moving down fracture footwalls and, locally, collecting on the floors of lithophysal cavities. Most UZ calcite $\delta^{13}\text{C}$ values, which are generally between -9 and +2‰, indicate derivation of solutes from the overlying soils during infiltration (fig. 1). Local occurrences of early calcite from UZ exposures in drill core and the Exploratory Studies Facility have anomalously heavy $\delta^{13}\text{C}$ values (as high as 9‰) that are inconsistent with soil organic matter as the sole carbon source.

Figure 1. Stable C and O isotopic compositions of calcite, plotted with respect to the water table, from boreholes collared on the crest or eastern flank of Yucca Mountain. Fields discussed in text are outlined and labeled.

Textures and compositions of calcite occurrences from deep in the SZ are distinctly different from those in the UZ. Deep SZ calcite occurs as tightly intergrown crystal masses that filled existing open spaces, replaced phenocrysts, and formed pore-filling cements. This SZ mineralization appears to have formed from moderate temperature alteration of the tuffs (Broxton et al., 1987) by Paleozoic ground waters that introduced calcite with $\delta^{13}\text{C}$ values of $0 \pm 2\%$ (Whelan et al., 1994). Timing of alteration is consistent with the formation of the Timber Mountain caldera (Bish and Aronson, 1993).

Secondary mineral occurrences formed in the UZ and the SZ are distinguished by the following characteristics:

- (1) *Textures/mineralogy* - UZ calcite occurs as free-growing crystals, with patchy chalcedony or drusy quartz in the early stage and with opal in the later stages. Alteration-event calcite, locally with banded chalcedony and quartz, formed interlocking crystal mosaics that filled SZ open spaces.
- (2) *UV fluorescence/phosphorescence* - Early UZ calcite does not fluoresce or phosphoresce nor does later calcite found at depth in the UZ; late UZ calcite fluoresces and phosphoresces bright white in occurrences from the near surface. Alteration-event calcite fluoresces bright orange but does not phosphoresce.
- (3) *Cathodoluminescence* - Calcite from the UZ generally does not luminesce but locally contains thin, irregular growth bands that luminesce faintly to moderately orange. Alteration-event calcite invariably luminesces a fiery bright orange.
- (4) *Fluid inclusions* - Calcite from the UZ has fluid inclusions that are typically single-phase, either all-liquid or all-vapor, indicative of entrapment in a UZ setting (Roedder et al., 1994). Alteration-event calcite contains dominantly two-phase inclusions indicative of moderate-temperature (94 to 239°C), SZ mineral growth (Bish and Aronson, 1993).
- (5) *Strontium isotopes* - $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcite samples display slightly overlapping ranges of 0.7096 to 0.7127 in the UZ and 0.7086 to 0.7098 in the SZ, and do not clearly differentiate between the UZ and SZ (Marshall et al., 1993).

Anomalous barren zone calcite occurrences from the upper SZ are outlined on figure 1. These anomalous occurrences range in depth from about 140 to about 300 m below the present water table and generally resemble UZ calcite because they: (1) are free-growing; (2) do not fluoresce or phosphoresce; (3) locally display orange growth banding but are largely nonluminescent; and (4), based on preliminary fluid inclusion observations, formed below -50°C in a vadose setting. Finally, (5) the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the calcite from these anomalous occurrences range from 0.7094 to 0.7104 ; although not definitive, these ratios are similar to the bulk rock compositions of the host rocks and could form during UZ conditions.

Based on these observations, the anomalous secondary mineral occurrences from the upper SZ appear to have formed under UZ conditions - lower water table elevations in the past is the most straightforward mechanism to explain an UZ setting at these depths. Other explanations involve movement of the tuff sequence relative to a more or less static water table position. For instance, past rates of tectonic uplift are unclear, as is the rate of isostatic crustal depression following eruption of the tuff sequence. Conceivably, such processes could have raised the tuff sequence with respect to a static water table.

The $\delta^{13}\text{C}$ values of the anomalous occurrences range widely from almost -10% to nearly $+5\%$. This range is comparable to the entire range of secondary calcite $\delta^{13}\text{C}$ values recorded by the more than 9 M.y. mineralization history of the UZ. The range of $\delta^{13}\text{C}$ values in this anomalous interval, therefore, may be evidence of more than one period of significantly lowered water table elevation.

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